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Adherend Thermal Effects During Bonding With Inductively Heated Films

by Eric D. Wetzel and Bruce K. Fink

ARL-TR-2461 April 2001

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Adherend Thermal Effects During Bonding With Inductively Heated Films

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Abstract

The thermal performance of an inductively heated film sandwiched between two identical adherends is investigated. Models for infinite conductivity finite thickness adherends, finite conductivity semi-infinite thickness adherends, and finite conductivity finite thickness adherends are presented. Calculations are performed for polymer-matrix composite, ceramic, and metal adherends for a variety of adherend thicknesses. The results show that for expected bonding applications, film heating rates will be reduced by a factor of 10–100, as compared with insulated film heating rates with no attached adherends. Higher reductions in heating performance are noted for ceramic and metal adherends as compared with composite adherends. However, even with the most severe reductions in heating rates, bonding with inductively heated films is feasible.

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1. Introduction

1.1 Motivation. The need to reduce weight and improve survivability in Army vehicle and weapons systems has led to increasing usage of polymer-matrix composites and ceramic materials for structural and armor applications. These materials, however, pose major challenges for integration into complex assemblies due to limitations in joining technology. Unlike metallic structures, which can be welded or fastened mechanically, composites and ceramics require surface bonding methods such as thermoplastic hot-melt bonding or adhesives. Since each material satisfies specific performance objectives, final assemblies will often involve multiple materials. This characteristic requires that composites and ceramics will be bonded to many different materials, including metals and other composites and ceramics.

Recent efforts have shown the potential of using inductively heated films for bonding [1]. A thermoplastic or adhesive is doped with micron-sized magnetic particles. In a high frequency magnetic field, these magnetic particles heat. This thermal energy melts the thermoplastic to form a hot-melt bond, or cures the adhesive. Because the films are generally thin and the magnetic field penetrates completely into the film, heating in the film is reasonably uniform.

For magnetic particle film bonding to be feasible, the film heating rate must be sufficient to generate the time-temperature profile required for a given bonding process. Wetzel and Fink [1] have predicted heating rates for magnetic particle films as a function of magnetic field characteristics and material properties. However, these predictions assume an insulated film with no thermal losses, so that the conductive losses into the adherends are neglected.

In this report we construct models to predict the effect of the adherends on the film heating performance. Because of the range of materials and plate thicknesses which will eventually be joined using this technology, a general model is derived which can be used as a design tool for future joining scenarios. Specific calculations are also provided for a wide range of likely adherend properties, to assess the order-of-magnitude effects of adherends on bondline processing.

1.2 Approach. Our objective is to assess the changes in bond processing caused by the presence of the adherend. The most relevant metric for quantification of magnetic particulate film heating performance is the bondline heating rate [1]. To calculate this metric, heat transfer solutions are derived or cited for the case of a volumetrically heated film attached to different classes of adherends in section 2. These models are used to calculate the heating rate at the bondline. Comparing these heating rates with the heating rates predicted for an insulated film with no attached adherend provides a quantitative measure of the effect of the adherend on the

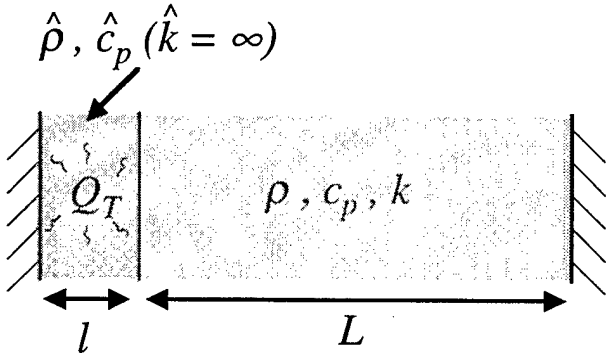

Figure 1. Schematic for Film / Adherend Heat Transfer Models.

bondline thermal processing. Such comparisons are provided for specific adherend materials and thicknesses in section 3, and a general discussion on the implications and applicability of these results is provided in section 4.

The model geometry we will use is shown in Figure 1. A volumetrically heated film of thickness l is insulated on one side and attached via a perfectly-conducting interface to a conductive adherend of thickness L. Although the film is a two-phase particulate composite, we will treat it as a uniform material with density, specific heat, conductivity, and thermal diffusivity denoted by $\hat{\rho}$, $\hat{c}_p$, $\hat{k}$, and $\hat{\alpha} \equiv \hat{k}/\hat{\rho}\hat{c}_p$, respectively. We assume that the film is sufficiently thin and conductive (small $l^2/\hat{\alpha}$) such that the temperature in the film is always uniform. More formally, we assume that $t_p \gg l^2/\hat{\alpha}$, where t_p is the process time scale. The film generates heating power per unit volume of $\bar{Q}_T \equiv Q_T/lA_x$, where A_x is the cross-sectional area of the film and Q_T is the total heating power in the film. The adherend has thermophysical properties ρ, c_p, k, and $\alpha \equiv k/\rho c_p$, and is insulated on its free face. The analysis is 1-D, so that both adherend and film are assumed to be infinite in cross-section.

The insulated film assumption can be interpreted in two ways. The most obvious interpretation is that the film is attached to a thermally insulating medium. The second interpretation is a symmetry boundary condition. If a film is placed symmetrically between two identical adherends, there is no heat flow across the sandwich centerline. Therefore our model results can be interpreted as the heating rates for a piece of film of thickness $2l$ sandwiched between two adherends composed of identical material, and each of thickness L.

Three different heat transfer models will be presented, each involving different physical assumptions. The first model (section 2.1) assumes finite adherend thickness, but infinite adherend conductivity. The temperature is assumed to be uniform in the adherend, so it only provides a lumped thermal mass in addition to that of the film itself. This solution is most

relevant to thin, highly conductive adherends or long process times. The second model (section 2.2) assumes a semi-infinite adherend thickness, and finite adherend conductivity. This solution is most relevant to thick, poorly conducting adherends or short process times. The third model (section 2.3) is the most general case, with finite adherend thickness and conductivity. The infinite conductivity and semi-infinite thickness adherend models are limiting cases of this general solution.

2. Bondline Heating Rate Solutions

In this section we present solutions for the bondline heating rates for three different adherend scenarios. Two of these solutions address limiting adherend characteristics: an adherend with infinite conductivity and finite thickness, and an adherend with finite conductivity and semi-infinite thickness. The third solution is the most general, for an adherend with finite conductivity and finite thickness.

2.1 Infinite Conductivity, Finite Thickness Adherend. To model thin, highly conductive adherends, in this section we solve for the heating rate for the case of an adherend with infinite conductivity, $k \to \infty$. In this case the temperature in both the film and adherend is uniform.

The total heating power generated in the film is

$$Q_T = \bar{Q}_T V_f = \bar{Q}_T A_x l \tag{1}$$

where V_f is the film volume. The heat capacity of the film can be written as

$$\text{film heat capacity} = \hat{\rho}\hat{c}_p V_f = \hat{\rho}\hat{c}_p A_x l \tag{2}$$

and the adherend heat capacity can be written as

$$\text{adherend heat capacity} = \rho c_p V_a = \rho c_p A_x L \tag{3}$$

Assuming uniform temperatures and heat generated only in the film, a lumped energy balance can be written as

$$\bar{Q}_T A_x l = \frac{dT}{dt}\left(\hat{\rho}\hat{c}_p A_x l + \rho c_p A_x L\right) \tag{4}$$

where T is the adherend temperature and t is time. Simplifying yields

$$\frac{\bar{Q}_T}{\hat{\rho}\hat{c}_p} = \frac{dT}{dt}\left(1 + \frac{\rho c_p L}{\hat{\rho}\hat{c}_p l}\right) \tag{5}$$

This equation can be rewritten as

$$\frac{dT}{dt} = \frac{\bar{Q}_T}{\hat{\rho}\hat{c}_p}\frac{H}{1+H} \tag{6}$$

where

$$\boxed{H \equiv \frac{\hat{\rho}\hat{c}_p l}{\rho c_p L}} \tag{7}$$

Wetzel and Fink [1] calculate the expected heating rates for magnetic particle films as a function of magnetic field strength and frequency, and polymer film and magnetic particle material properties. The heating rates are derived assuming an insulated film with no attached adherend, with the result expressed as

$$\frac{dT}{dt} = \frac{\bar{Q}_T}{\hat{\rho}\hat{c}_p} \tag{8}$$

where $\bar{Q}_T$ is determined by the specific film material system and magnetic field characteristics under consideration. For comparison with these insulated, isolated film heating rates, it will be useful to define the reduced heating rate

$$R_{\text{rate}} \equiv \frac{\text{Heating rate with adherend}}{\text{Heating rate without adherend}} \tag{9}$$

$$\equiv \frac{\text{Heating rate with adherend}}{\bar{Q}_T/\hat{\rho}\hat{c}_p} \tag{10}$$

Using equation 6, the reduced heating rate for an adherend with infinite conductivity is

$$\boxed{R_{\text{rate}} = \frac{H}{1+H}} \tag{11}$$

Figure 2 shows R_{rate} as a function of H.

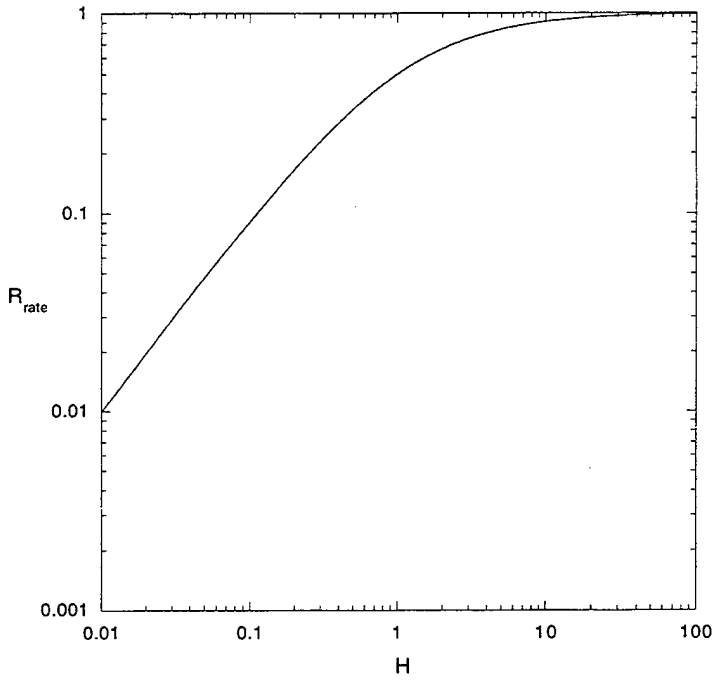

Figure 2. Reduced Heating Rate as a Function of H for Infinite Conductivity Adherend Solution.

2.2 Finite Conductivity, Semi-Infinite Thickness Adherend. Thick adherends can be approximately modeled by assuming a semi-infinite adherend, $L \to \infty$. The transient temperature profile in such an adherend, for the case of a perfectly-attached, thin, infinite conductivity, heat-generating film, is given by Trankle [2] (as cited in Carslaw and Jaeger [3]) as

$$T(x,t) = T_i + \frac{\bar{Q}_T}{\hat{\rho}\hat{c}_p} G \frac{l^2}{\alpha} \left[\frac{1}{\sqrt{\pi}} \frac{2\sqrt{\alpha t}}{l} e^{-\frac{x^2}{4\alpha t}} - \left(G + \frac{x}{l}\right) \operatorname{erfc} \frac{x}{2\sqrt{\alpha t}} + G e^{\left(\frac{1}{G}\frac{x}{l} + \frac{1}{G^2}\frac{\alpha t}{l^2}\right)} \operatorname{erfc}\left(\frac{x}{2\sqrt{\alpha t}} + \frac{1}{G}\frac{\sqrt{\alpha t}}{l} \right) \right] \tag{12}$$

where

$$\boxed{G \equiv \frac{\hat{\rho}\hat{c}_p}{\rho c_p}} \tag{13}$$

T_i is the initial, uniform temperature in the adherend, and x is the spatial coordinate in the thickness direction, with $x = 0$ at the film / adherend interface. We are only interested in the

temperature at this interface, where

$$T(0,t) = T_i(0) + \frac{l^2 \bar{Q}_T}{k}\left[\frac{1}{\sqrt{\pi}}\frac{2\sqrt{\alpha t}}{l} - G + Ge^{(\frac{1}{G^2}\frac{\alpha t}{l^2})}\text{erfc}\frac{1}{G}\frac{\sqrt{\alpha t}}{l}\right] \tag{14}$$

We can rewrite this equation as

$$T(0,t) = T_i(0) + \frac{l^2 \bar{Q}_T}{k}\left[\frac{1}{\sqrt{\pi}}2G\sqrt{\frac{t}{\tau_i}} - G + Ge^{(t/\tau_i)}\text{erfc}\sqrt{\frac{t}{\tau_i}}\right] \tag{15}$$

where

$$\boxed{\tau_i = G^2\frac{l^2}{\alpha}} \tag{16}$$

The heating rate at the film / adherend interface can be calculated by differentiating equation 15 with respect to time, giving

$$\frac{dT}{dt}(0,t) = \frac{l^2 \bar{Q}_T}{k}\frac{G}{\tau_i}e^{(t/\tau_i)}\text{erfc}\sqrt{\frac{t}{\tau_i}} \tag{17}$$

Using equation 10, we can write the reduced heating rate for the case of the semi-infinite adherend as

$$R_{\text{rate}} = \frac{l^2 \hat{\rho}\hat{c}_p}{k}\frac{G}{\tau_i}e^{(t/\tau_i)}\text{erfc}\sqrt{\frac{t}{\tau_i}} \tag{18}$$

or

$$\boxed{R_{\text{rate}} = e^{(t/\tau_i)}\text{erfc}\sqrt{\frac{t}{\tau_i}}} \tag{19}$$

This equation gives the reduced heating rate for the case of a semi-infinite adherend. Figure 3 gives R_{rate} as a function of reduced time t/τ_i, as calculated through equation 19.

2.3 Finite Conductivity, Finite Thickness Adherend. The most general solution models an adherend with finite thickness L and finite conductivity k. The adherend is insulated at $x = L$, and at $x = 0$. A perfectly-attached, thin, infinite conductivity, heat-generating film is bonded to the adherend at $x = 0$, and the adherend is insulated at $x = L$.

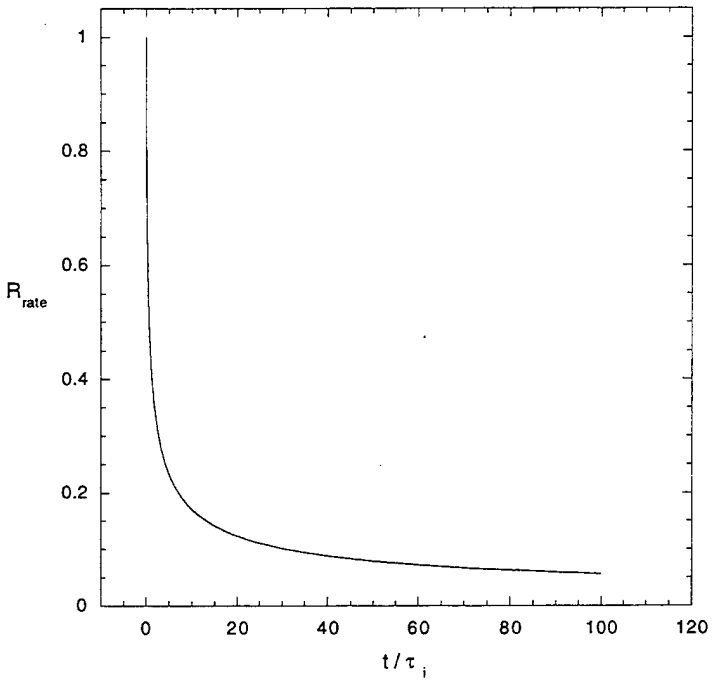

Figure 3. Reduced Heating Rate as a Function of t/τ_i for Semi-Infinite Adherend Solution.

The transient temperature profile for this case is given by Carslaw and Jaeger [4] as

$$T(x,t) = T_i + \frac{\bar{Q}_T}{\hat{\rho}\hat{c}_p} H\tau_f \left\{ \begin{array}{r} -\frac{1}{6}\frac{1+3H}{(1+H)^2} + \frac{1}{2}\frac{(1-x/L)^2}{1+H} + \frac{t/\tau_f}{1+H} \\ - \sum_{k_n>0} \frac{4\cos(k_n[1-x/L])}{k_n^2(H+H^2k_n^2+1)\cos k_n} e^{-k_n^2 t/\tau_f} \end{array} \right\} \tag{20}$$

where the dimensionless parameter H was defined in equation 7 and

$$\boxed{\tau_f \equiv L^2/\alpha} \tag{21}$$

k_n are the roots to the transcendental equation

$$\boxed{\tan k_n + Hk_n = 0} \tag{22}$$

For our adherend studies, we are only interested with the temperature at the film / adherend interface, $x = 0$, where

$$T(0,t) = T_i + \frac{\bar{Q}_T}{\hat{\rho}\hat{c}_p} H\tau_f \left\{ \begin{array}{r} -\frac{1}{6}\frac{1+3H}{(1+H)^2} + \frac{1}{2}\frac{1}{1+H} + \frac{t/\tau_f}{1+H} \\ - \sum\limits_{k_n>0} \frac{2}{k_n^2(H+H^2k_n^2+1)} e^{-k_n^2 t/\tau_f} \end{array} \right\} \tag{23}$$

The heating rate at the film / adherend interface can be calculated by differentiating equation 23 with respect to time, giving

$$\frac{dT}{dt}(0,t) = \frac{\bar{Q}_T}{\hat{\rho}\hat{c}_p} H\tau_f \left\{ \frac{1/\tau_f}{1+H} - \sum_{k_n>0} \frac{-2k_n^2/\tau_f}{k_n^2(H+H^2k_n^2+1)} e^{-k_n^2 t/\tau_f} \right\} \tag{24}$$

or

$$\frac{dT}{dt}(0,t) = \frac{\bar{Q}_T}{\hat{\rho}\hat{c}_p} \left\{ \frac{H}{1+H} + \sum_{k_n>0} \frac{2H}{(H+H^2k_n^2+1)} e^{-k_n^2 t/\tau_f} \right\} \tag{25}$$

Using equation 10, we can write the reduced heating rate for the case of the semi-infinite adherend as

$$\boxed{R_{\text{rate}} = \frac{H}{1+H} + \sum_{k_n>0} \frac{2H}{(H+H^2k_n^2+1)} e^{-k_n^2 t/\tau_f}} \tag{26}$$

Figure 4 shows R_{rate} as a function of reduced time t/τ_f and H, calculated using equation 26 (summing to 500 roots using Mathematica®). Note that smaller values of H cause a greater reduction in heating rate, and that at long times the reduced heating rate approaches a constant value. Figure 5 superimposes the general solution on top of the solution for a semi-infinite thickness adherend, equation 19, and a finite thickness infinite conductivity adherend, equation 11. To make the comparison with the semi-infinite adherend, we utilize the transformation

$$\tau_i = H^2\tau_f \tag{27}$$

to calculate R_{rate} in equation 19 as a function of τ_f and H. For small times, $t < 0.1\tau_i$, the general solution matches the semi-infinite thickness solution. For large times, $t > \tau_i$, the general solution matches the infinite conductivity solution. These observations show that the semi-infinite thickness solution is the short time model of the general problem, while the infinite conductivity model is the long time model of the general problem.

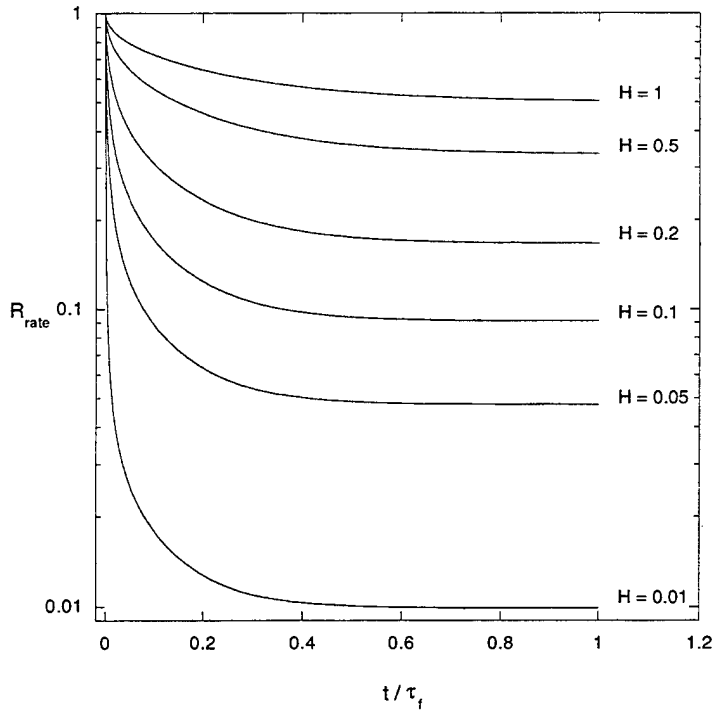

Figure 4. Reduced Heating Rate as a Function of t/τ_f and H for Finite Adherend Solution.

3. Calculations

In this section we perform heating rate calculations, using the models derived in section 2, for specific, likely adherend materials and thicknesses and likely film materials and thicknesses. The applicability of each result is discussed in more detail in section 4.1.

3.1 Material Properties. For our induction bonding application, the volumetrically heating film is a particulate composite composed of magnetic particles dispersed in a polymer matrix. The thermophysical properties of this film can be calculated from the component material properties using a simple volume averaging approach

$$\hat{\rho} = v_f \rho + (1 - v_f)\tilde{\rho} \tag{28}$$

$$\hat{c}_p = v_f c_p + (1 - v_f)\tilde{c}_p \tag{29}$$

where v_f is the particle volume fraction, ρ and c_p are particle properties, and $\tilde{\rho}$ and $\tilde{c}_p$ are matrix properties. Since we have assumed uniform temperature in the film, the film conductivity and thermal diffusivity are not relevant. For specific calculations, we will use a promising material system identified by Wetzel and Fink [1] which contains 15% by volume nickel zinc ferrite.

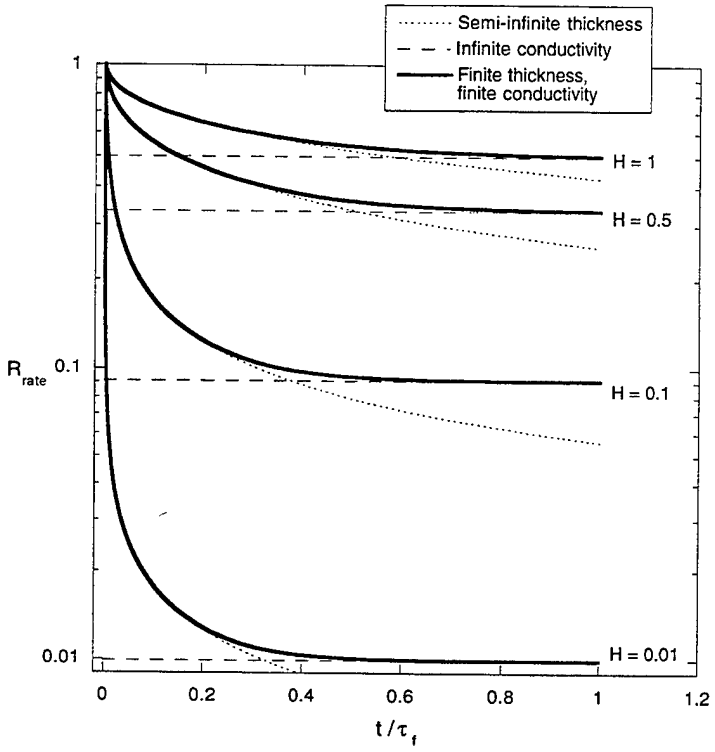

Figure 5. Reduced Heating Rate as a Function of t/τ_f and H for Finite Adherend Solution, with Superimposed Semi-Infinite Thickness Adherend Model and Infinite Conductivity Solution.

Table 1. Film Component and Composite Material Properties. Polymer properties are typical for engineering thermoplastics and adhesives. Nickel zinc ferrite properties from Snelling [5]. Film properties calculated using equations 28 and 29 with a particle volume fraction of $v_f = 15\%$.

	Polymer	NiZn Ferrite	Composite Film
Density, $\hat{\rho}$ (kg/m^3)	1000	4500	1525
Specific Heat, $\hat{c}_p$ (J/kg K)	1000	750	963

Table 2. Adherend Thermophysical Properties. Polymer composite properties typical for engineering polymers. Ceramic properties (alumina) from Sheppard [6]. Metal properties (aluminum) from Ozisik [7].

	Composite	Ceramic	Metal
Density, ρ (kg/m^3)	1000	3900	2700
Specific heat, c_p (J/kg K)	1000	1000	900
Thermal conductivity, k (W/m K)	0.2	30	200
Thermal diffusivity, $\alpha \equiv k/\rho c_p$ (m^2/s)	2.0×10^{-7}	7.7×10^{-6}	8.2×10^{-5}

Table 1 gives the material properties for the individual components and the 15% particulate composite film.

The range of potential adherend materials used in applications includes polymer composite, ceramic, and metal. For composite materials, we will use the typical polymer material properties given in Table 2. Steel and aluminum are both candidate metal materials for armor applications. We will use aluminum properties for our representative metal adherend, as its higher thermal conductivity will provide a more extreme bound on possible adherend thermal loss effects. The aluminum thermophysical properties are given in Table 2. Two common ceramics used in armor applications are alumina and silicon carbide. The density and heat capacity of these materials are similar, but their thermal conductivities vary by an order of magnitude, with a value of $\sim$ 30 W/m K for alumina and 270 W/m K for silicon carbide. We will use alumina as our model ceramic, since it provides a more intermediate value between the cases of metal and polymeric composite. However, the reader is cautioned to check material properties carefully before using the results calculated in later sections, as the high thermal conductivity of some ceramics may make them closer to our representative "metal" material properties than to our "ceramic" material properties. The full alumina thermophysical properties are given in Table 2.

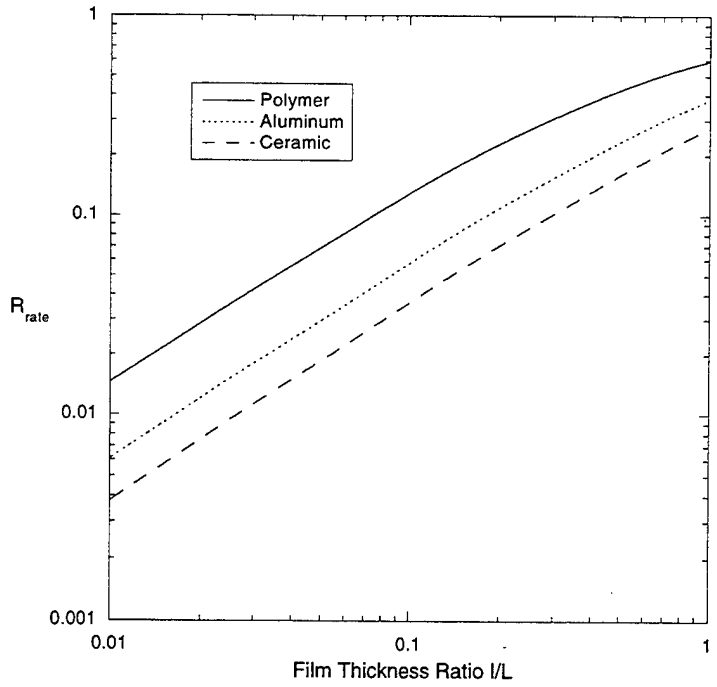

Figure 6. Reduced Heating Rate as a Function of Film Thickness Ratio l/L for Various Adherend Materials and Infinite Conductivity Adherend Solution.

3.2 Bondline Heating Rates for Specific Material Systems.

3.2.1 Infinite Conductivity Adherend. Equation 11 predicts the reduced heating rate for a film in contact with an adherend with infinite conductivity. Using this model, Figure 6 shows R_{rate} as a function of film thickness ratio l/L for each adherend material in Table 2. Note that a ceramic adherend reduces the heating rate more than an aluminum adherend of identical thickness. This result occurs because, if the adherend is assumed to be at uniform temperature, thermal conductivity is no longer a relevant physical parameter. The reduction in heating rates is caused completely by heat capacity effects, and for our material properties the ceramic has a higher heat capacity than the aluminum. The plots also show that for film thickness ratios between 0.01 and 0.1, the adherend will reduce the insulated film heating rate by a factor of 10 to 100.

3.2.2 Semi-Infinite Thickness Adherend. Equation 19 predicts the reduced heating rate for a film in contact with an adherend with semi-infinite thickness. Unlike the infinite conductivity results of section 3.2.2, we cannot define a thickness ratio since the adherend thickness is not finite. Therefore, for adherend material studies, we are forced to calculate reduced heating

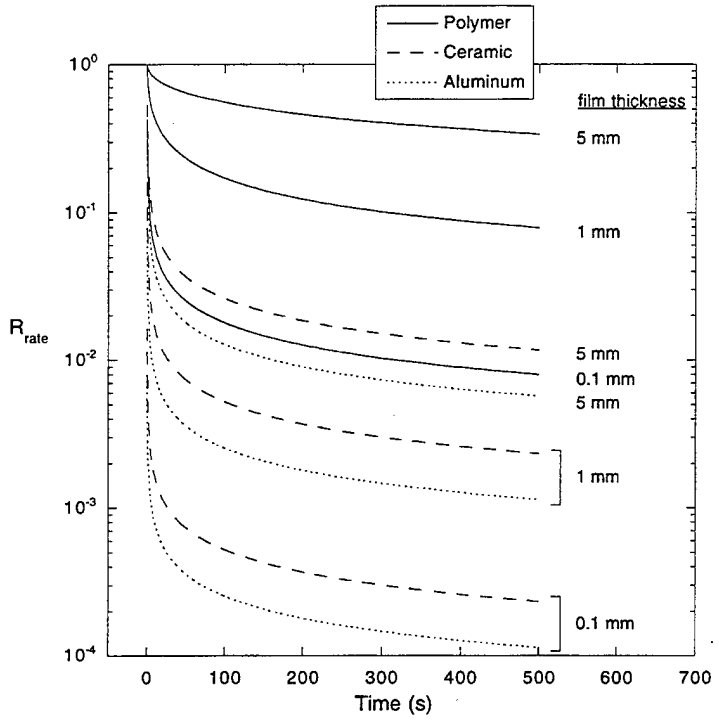

Figure 7. Reduced Heating Rate as a Function of Time and Film Thickness for Various Adherend Materials and Semi-Infinite Adherend Solution.

rates for specific film thicknesses. Equation 19 also shows that the reduced heating rate is a function of time. Figure 7 shows reduced heating rate as a function of film thickness and time, for the adherend materials of Table 2. The same data is presented in Figure 8, but allows easier interpretation as time for heating rate to be reduced to a given R_{rate} as a function of film thickness. Note that for a low conductivity adherend, such as a polymer composite, the heating rate will be reduced by a factor of 10 in under a minute, and by as much as 100 after a few minutes. For higher conductivity materials, such as aluminum, the thermal loss is more severe, reducing the heating rate to 1/1000 of its insulated value in under one minute. However, as will be discussed in section 4.1, these results are only applicable to high conductivity materials such as aluminum if the adherend is extremely thick.

*3.2.3 **Finite Thickness, Finite Conductivity Adherend.*** Equation 26 predicts the reduced heating rate for a film in contact with an adherend with finite thickness and finite conductivity. Figures 9 – 11 show the reduced heating rate as a function of time and adherend thickness, for film thicknesses of 0.1 mm, 1 mm, and 5 mm, respectively. The adherend material properties are given by Table 2, and equation 26 is implemented by summing to 500 roots using Mathematica®.

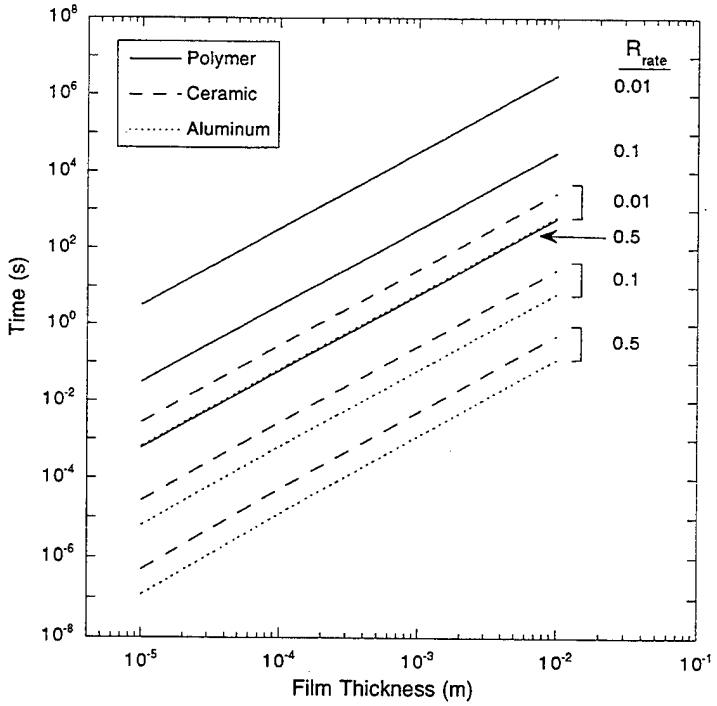

Figure 8. Time to Achieve Reduced Heating Rates as a Function of Film Thickness for Various Adherend Materials and Semi-Infinite Adherend Solution.

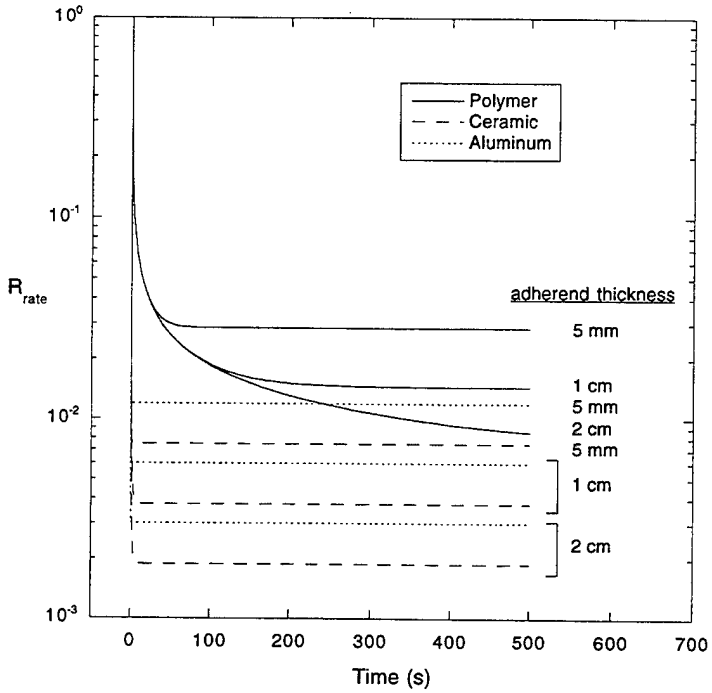

Figure 9. Reduced Heating Rate as a Function of Time and Adherend Thickness for Various Adherend Materials, with 0.1 mm Film Thickness and Finite Adherend Solution.

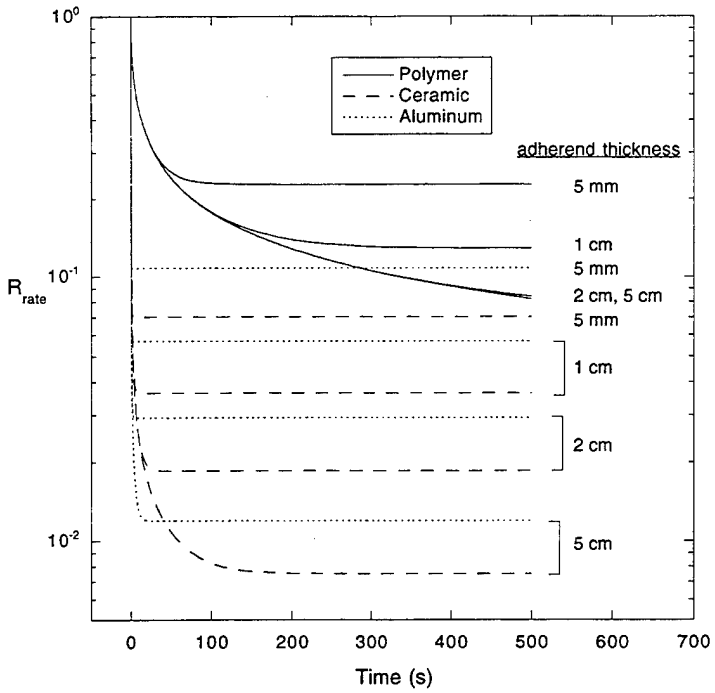

Figure 10. Reduced Heating Rate as a Function of Time and Adherend Thickness for Various Adherend Materials, with 1 mm Film Thickness and Finite Adherend Solution.

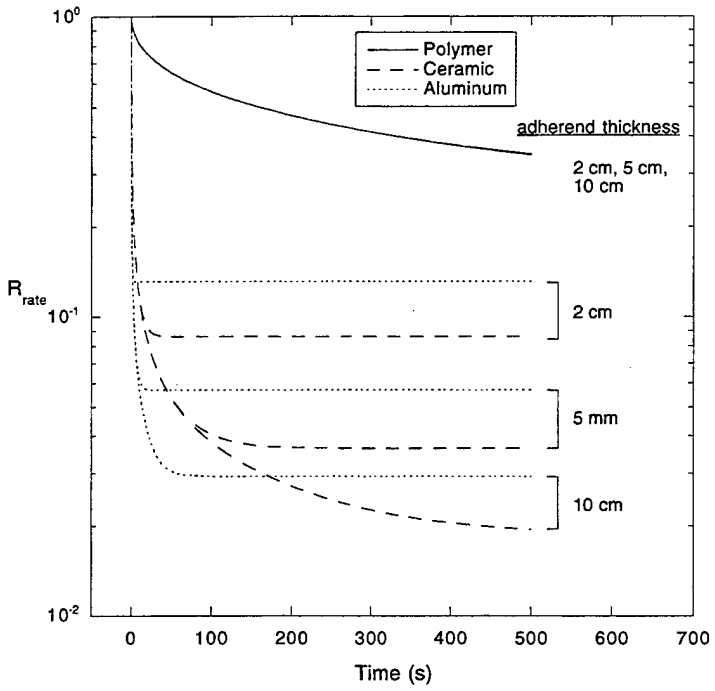

Figure 11. Reduced Heating Rate as a Function of Time and Adherend Thickness for Various Adherend Materials, with 5 mm Film Thickness and Finite Adherend Solution.

First consider the case of a 0.1 mm film thickness, Figure 9. The adherend thicknesses shown, 5 mm, 1 cm, and 2 cm, are relatively thin adherends since the film thickness is also thin. For the aluminum and ceramic cases, note that the heating rate drops to the infinite conductivity solution value within seconds. For a 5 mm thick adherend, the heating rate is reduced by a factor of 100. For the thicker adherends, the heating rate reduction approaches a factor 1000. Note that in all cases the ceramic adherend results in a lower effective heating rate than the aluminum adherend. This behavior occurs because the adherends closely follow the infinite conductivity solution, which is governed by specific heat. For the thickest polymer adherend, 2 cm, the results closely follow the infinite adherend solution through 500 s. For the thinner adherends, the infinite conductivity solution is reached at large times, > 300 s. For all of the polymer adherend thicknesses, the heating rate is reduced by roughly a factor of 100.

Figure 10 shows the reduced heating rates for the case of a 1 mm film. The adherend thicknesses used are 5 mm, 1 cm, 2 cm, and 5 cm. The behavior is qualitatively similar to that of the 0.1 mm adherend, except that the heating rates are a factor of 10 greater. The aluminum and ceramic adherends reduce the heating rates by a factor of 10-100, while the polymer adherends reduce the heating rates by roughly a factor of 10. Again, ceramic adherends present a greater heat sink than the aluminum adherends.

Figure 11 shows the reduced heating rates for the case of a 5 mm film. Since this is a very thick film, the adherend thickness used are 2 cm, 5 cm, and 10 cm. Note that, because of the thickness of the polymer adherends, all cases obey the semi-infinite thickness model. The aluminum and ceramic adherends span the semi-infinite thickness and infinite conductivity solutions, depending on their thickness and the process time. Note that for the thicker adherends, initially the aluminum adherend presents a greater heat sink but at longer times the ceramic becomes a greater heat sink. The polymer adherends reduce the heating rates by up to a factor of 7, while the aluminum and ceramic adherends reduce the heating rates by a factor of 10-100.

4. Analysis and Conclusions

4.1 Model Applicability. In section 3.2 we calculated reduced heating rates for a variety of adherend materials using three different heat transfer models. The model used in section 3.2.3 is most general, and applies to any adherend with finite conductivity and thickness. The models of sections 3.2.1 and 3.2.2 are only applicable under conditions of infinite adherend conductivity and thickness, respectively. Since, in practice, we do not ever encounter adherends with truly infinite conductivity or thickness, we need to establish a criterion for

determining the applicability of these models to a given adherend. This criterion is the characteristic thermal conduction time.

We define the characteristic thermal conduction time for an adherend as

$$t_c = \frac{L^2}{\alpha} \tag{30}$$

Note that t_c is equivalent to τ_f defined by equation 21. t_c is roughly the amount of time required for a significant amount of thermal energy to transport the distance L in a material with thermal diffusivity α. For times much less than the characteristic thermal conduction time, $t \ll t_c$, significant thermal energy does not reach the insulated face of the adherend, so the semi-infinite adherend solution models the behavior accurately. For times much greater than the characteristic thermal conduction time, $t \gg t_c$, thermal diffusion occurs very rapidly, so the infinite adherend conductivity solution models the behavior accurately. If $t \sim t_c$, then only the general finite thickness, finite conductivity model will be accurate. These short-time, long-time solution relationships were shown graphically in Figure 5.

To evaluate model applicability for a specific adherend material and thickness, equation 30 should be used to calculate the characteristic conduction times. This approach provides a design tool for specific process prediction. For the purpose of general adherend material assessment, we will find it more appropriate to choose a characteristic processing time, and then calculate a characteristic conduction length. Based on equation 30, we define the characteristic thermal conduction length as

$$L_c = \sqrt{\alpha \cdot \text{process time}} \tag{31}$$

Thermal conduction length, for a given process time, is a material parameter independent of adherend thickness. If an adherend thickness is much less than its characteristic conduction length, $L \ll L_c$, then $t \gg t_c$ and the infinite conductivity solution applies. If an adherend thickness is much greater than its characteristic conduction length, $L \gg L_c$, then $t \ll t_c$ and the semi-infinite adherend solution applies. If $L \sim L_c$, then $t \sim t_c$ and only the general solution will predict accurate heating rates.

Table 3 gives characteristic thermal conduction lengths for each adherend material in Table 2 and for a typical process time of 100 s. Using these results, we can assess the applicability of each model to each adherend material. The infinite conductivity model is most applicable to the metal adherend, and should be accurate for adherend thicknesses much less than 9 cm. For structural metal and light armor, with a thickness of only a few centimeters, this assumption

Table 3. Adherend Characteristic Conduction Lengths, as defined by equation 31, for a process time of 100 s.

	Composite	Ceramic	Metal
Char. conduction length	4.47 mm	2.8 cm	9.1 cm

should be accurate. The semi-infinite adherend thickness model is most applicable to the composite adherend, which has a low thermal conductivity and an L_c of only 4 mm. For a typical 1 or 2 cm composite structural or armor panel, this model should prove accurate. The thermal conduction length of the alumina ceramic is 3 cm, which is very close to the actual ceramic tile armor dimensions. Therefore it is most likely that the finite thickness, finite conductivity approach is the only model which will give accurate results for ceramic armor adherends.

4.2 Effect of Adherends on Feasibility of Bonding with Magnetic Particle Films.

Wetzel and Fink [1] have performed a feasibility study for bonding with magnetic particle films, considering both thermoplastic hot-melt bonding and elevated temperature adhesive bonding. Typical thermoplastic hot-melt bonding requires high temperatures (250−400° C) to ensure bond integrity but short process times (under 1 minute at processing temperature) to prevent thermal degradation [8]. This processing requires film heating rates of $10 - 100$°C/s. Elevated temperature accelerated adhesive bonds, which involve lower processing temperatures ($100 - 180$°C) and longer process times (5 - 20 minutes), only require heating rates of $1 - 10$°C/s.

Wetzel and Fink [1] also provide predictions of heating rates for insulated magnetic particle films with no adherends. As a benchmark, we will use a 15% NiZn ferrite / polymer film. From Wetzel and Fink [1], the expected heating rates for an insulated film of this composition are given in Table 4 for field frequencies of 100 kHz, 1 MHz, and 10 MHz. Also shown in the table are the heating rates expected if the film is sandwiched between two identical adherends of various materials. A typical film thickness of 1 mm (half film thickness $l = 0.5$ mm) and adherend thickness of 2 cm are used for the calculations, and heating rate reductions are calculated using the finite thickness model of section 2.3.

These heating rates results show that thermoplastic hot-melt bonding is marginally feasible with all adherends at high frequencies (10 MHz), and still feasible with thick composite adherends at moderate (1 MHz) frequencies. For elevated temperature adhesive bonding, composite adherends should be feasible even at low (100 kHz) frequencies, while metal and ceramic adherends should be feasible at higher (> 1 MHz) frequencies.

Table 4. Expected Heating Rates for 15% NiZn Ferrite / Polymer Film with Thickness $2l$ = 1 mm Sandwiched Between Two Identical Adherends of Various Materials.

Frequency	10 kHz	1 MHz	10 MHz
No adherend (insulated)	12 °C/s	120 °C/s	1200 °C/s
2 cm composite (after 1 minute)	1.2 °C/s	12 °C/s	120 °C/s
2 cm composite (after 5 minutes)	0.6 °C/s	6 °C/s	60 °C/s
2 cm ceramic	0.12 °C/s	1.2 °C/s	12 °C/s
2 cm aluminum	0.18 °C/s	1.8 °C/s	18 °C/s

The specific results presented in this section and in Table 4 are, of course, very limited. Only a few very specific adherend and film materials and thicknesses were taken into consideration. Additionally, the insulated film heating rates predicted in Wetzel and Fink [1] are only expected to be accurate to within one or two orders of magnitude. For more specific bonding design guidance, calculations should be performed for the materials and geometry under consideration, and experimentally measured film heat generation rates. However, these results do confirm the general feasibility of using magnetic particle films for bonding structural and armor components of various materials, including ceramics, metals, and polymer matrix composites.

4.3 Extension of Results to Non-Symmetric Adherends. The results derived in this report are strictly applicable to symmetric adherends only. That is, only bonding of two identical adherends (both in thickness and material properties) can be modeled. However, many magnetic particle film bonds will be performed on unsymmetric adherends. Examples include ceramic-composite bonds in multi-functional armor and metal-composite bonds for steel-framed composite shell vehicles. The solutions from this report certainly provide bounds on heating rates. A composite to ceramic bond will behave somewhere between a composite-composite and a ceramic-ceramic bond. Deriving a full, general, unsymmetric solution is possible but will be mathematically difficult. Wetzel [9] provides closely related solutions, for the case of negligible film thermal mass. A much simpler approach is to numerically solve for specific non-symmetric adherend cases, using for example a finite difference solution. It may also be possible to demonstrate a simple empirical rule for unsymmetric adherends based on the symmetric adherend solutions. For example, calculating R_{rate} independently for each adherend using the symmetric adherend solution and then using some sort of averaging approach to estimate the unsymmetric adherend solution. The investigation of unsymmetric adherends remains a topic for future investigation.

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The thermal performance of an inductively heated film sandwiched between two identical adherends is investigated. Models for infinite conductivity finite thickness adherends, finite conductivity semi-infinite thickness adherends, and finite conductivity finite thickness adherends are presented. Calculations are performed for polymer-matrix composite, ceramic, and metal adherends for a variety of adherend thicknesses. The results show that for expected bonding applications, film heating rates will be reduced by a factor of 10–100, as compared with insulated film heating rates with no attached adherends. Higher reductions in heating performance are noted for ceramic and metal adherends as compared with composite adherends. However, even with the most severe reductions in heating rates, bonding with inductively heated films is feasible.

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